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## COMPARATIVE MODELING OF InP SOLAR CELL STRUCTURES

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This work describes the comparative modeling of  $p^+n$  and  $n^+p$  indium phosphide solar cell structures using a numerical program PC-1D. The optimal design study has predicted that the  $p^+n$  structure offers improved cell efficiencies as compared to  $n^+p$  structure, due to higher open-circuit voltage. The various cell material and process parameters to achieve the maximum cell efficiencies are reported. The effect of some of the cell parameters on InP cell I-V characteristics has been studied. The available radiation resistance data on  $n^+p$  and  $p^+n$  InP solar cells are also critically discussed.

### INTRODUCTION

Recently indium phosphide has emerged as an attractive material for space power applications. Keavney et al. (ref. 1) have been successful in fabricating the highest efficiency (19.1% AM0 at 25°C) homoepitaxial  $n^+p$  InP solar cells using the MOCVD growth technique. To date a majority of the work has been devoted to the development of  $n/p$  type cells and very limited work has been reported on  $p/n$  type InP cells. In spite of the various reasons which might have hampered the work on the development of  $p/n$  type cells, the results of initial R&D work reported in references 2 and 3 have been quite encouraging. LPE and MOCVD growth techniques have been used to fabricate  $p/n$  cells and laboratory efficiencies as high as 15.9% AM0 have been achieved by Choi et al. (ref. 3). During the last few years no work on  $p/n$  cells has been reported. The aim of this study is to compare the optimally designed performance of  $n^+p$  and  $p^+n$  InP solar cells. PC-1D, a one-dimensional numerical program (ref. 4) has been used to model the two structures considered in this work. The effect of minority carrier diffusion lengths on  $p^+n$  InP cell performance have been considered. The scope of this paper does not allow for discussion of the complete parametric study and a critical comparison with the various modeling studies available in the literature. This work will be reported in a future paper. The radiation resistance of  $p/n$  and  $n/p$  InP cells has been compared and the results indicate the need for a systematic reevaluation of the comparative radiation resistance of the two InP cell configurations.

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## MODELING APPROACH

The PC-1D computer program developed by Basore et al. (ref. 4) was used to model and optimally design  $n^+p$  and  $p^+n$  InP solar cells. This one-dimensional program solves the standard semiconductor device equations a finite-element method. Relevant InP solar cell material and process parameters have been varied to arrive at the maximum cell performance. The effect of a single parameter on the cell I-V characteristics has been studied by varying the parameter of interest and keeping all other parameters constant.

## RESULTS AND DISCUSSION

Figure 1 and 2 show the calculated current-voltage characteristics (AM0, 1 sun,  $137.2 \text{ mW/cm}^2$ ,  $25^\circ\text{C}$ ) for the  $p^+n$  and  $n^+p$  InP solar cell

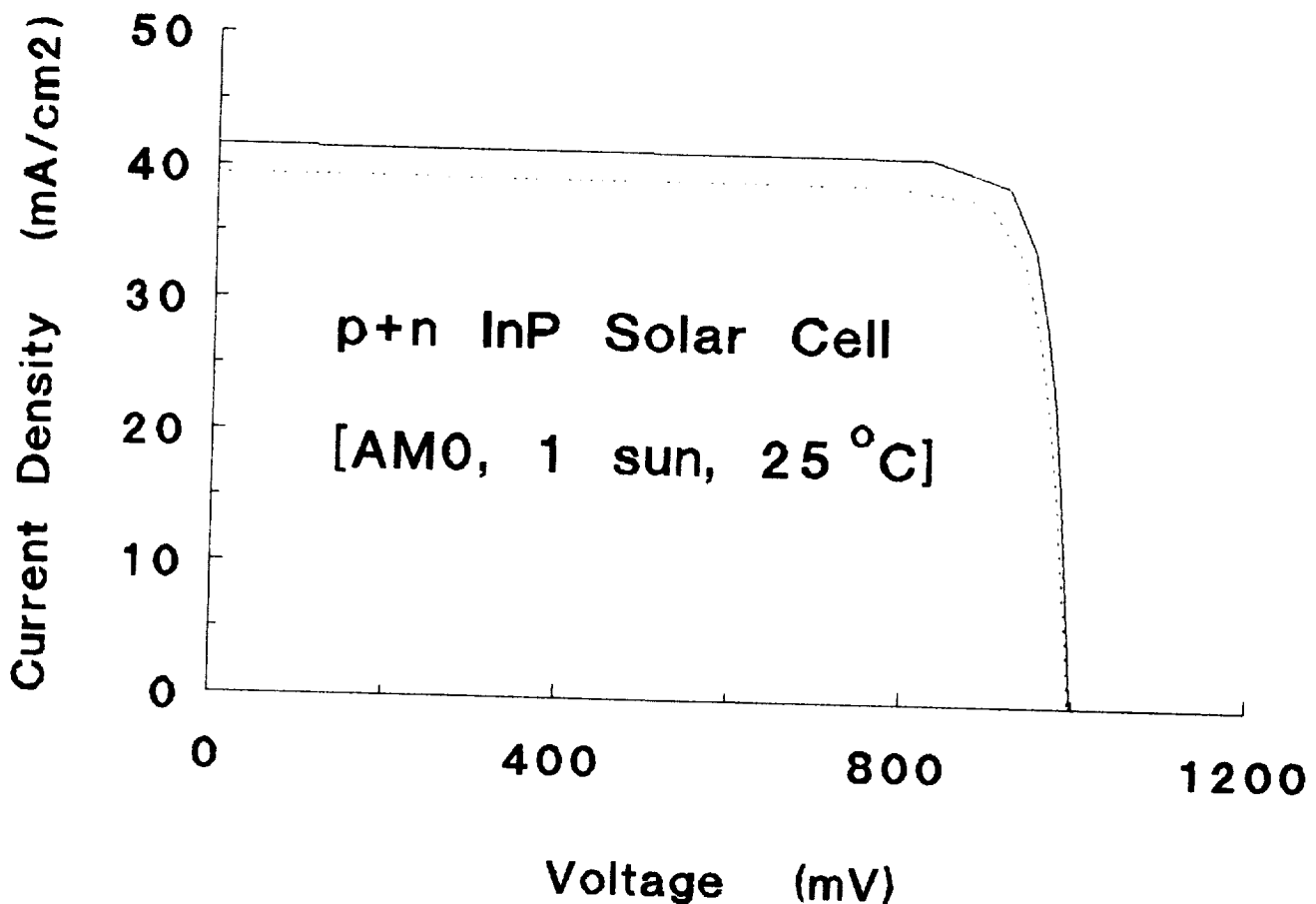


Fig. 1 Calculated I-V Characteristics of Optimally Designed  $p^+n$  InP Solar Cells. The Solid Line Curve ( $J_{sc}=41.49 \text{ mA/cm}^2$ ,  $V_{oc}=998 \text{ mV}$ ,  $FF=0.869$ ,  $Eff=26.2\%$ ) is for Grid Shadowing Loss of 0% and Series Resistance of  $0.1 \text{ ohm cm}^2$ . The Dotted Line Curve ( $J_{sc}=39.35 \text{ mA/cm}^2$ ,  $V_{oc}=996 \text{ mV}$ ,  $FF=0.867$ ,  $Eff=24.8\%$ ) is for Grid Shadowing Loss of 5% and Series Resistance of  $0.3 \text{ ohm cm}^2$ . The other parameters are as per Table I.

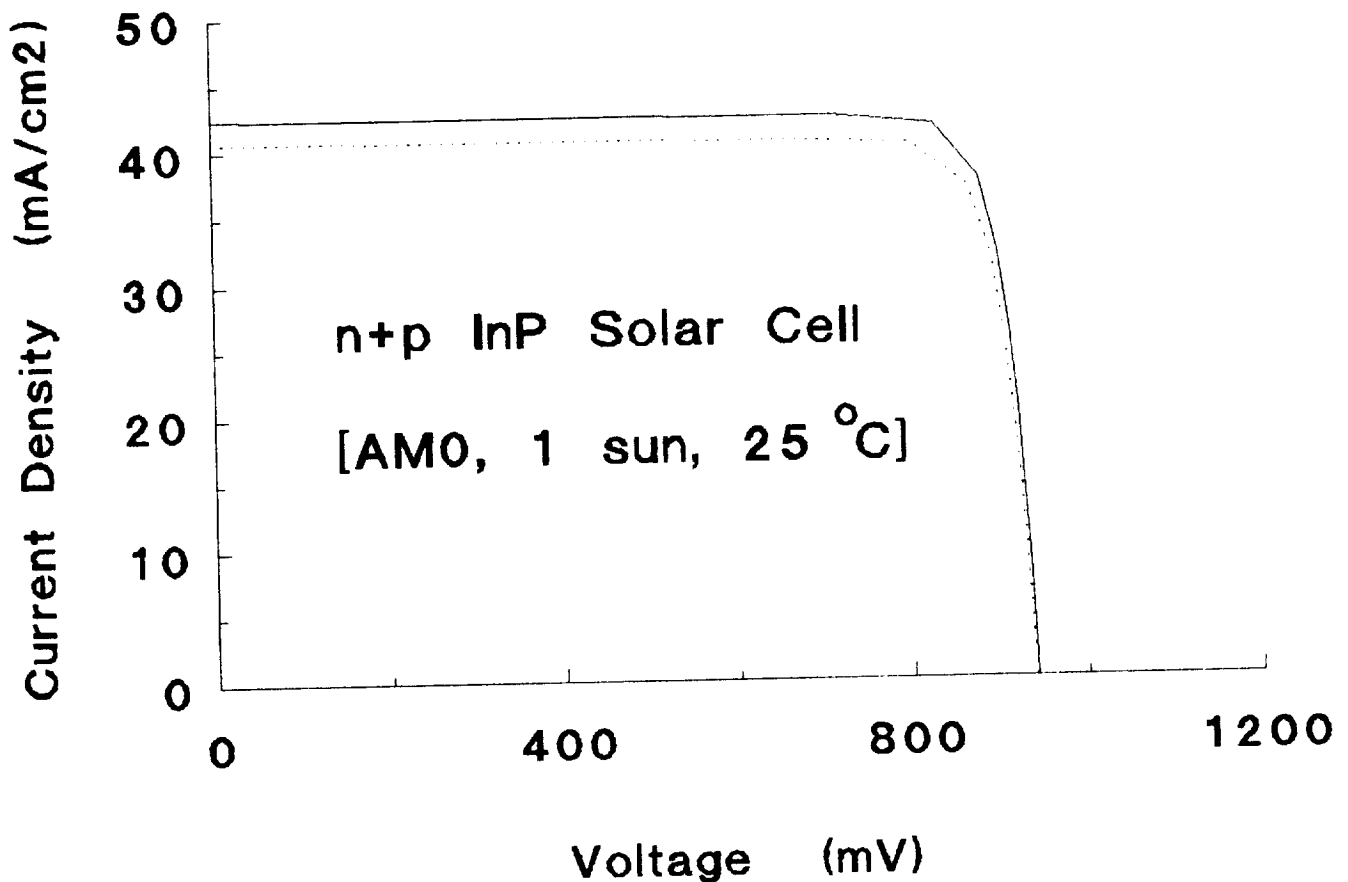


Fig. 2 Calculated I-V Characteristics of Optimally Designed n<sup>+</sup>p InP Solar Cells. The Solid Line Curve ( $J_{sc}=42.4$  mA/cm<sup>2</sup>,  $V_{oc}=941$  mV, FF=0.863, Eff=25.1%) is for Grid Shadowing Loss of 0% and Series Resistance of 0.1 ohm cm<sup>2</sup>. The Dotted Line Curve ( $J_{sc}=40.6$  mA/cm<sup>2</sup>,  $V_{oc}=940$  mV, FF=0.845, Eff=23.5%) is for Grid Shadowing Loss of 4% and Series Resistance of 0.2 ohm cm<sup>2</sup>. The other parameters are as per Table I.

configurations by solid lines respectively. The material and cell process parameters for the optimal design of p<sup>+</sup>n and n<sup>+</sup>p structures are described in Table I. From Table I following observations are made. The emitter of the n<sup>+</sup>p InP solar cell structure (20 nm) is relatively shallower than the p<sup>+</sup>n structure (0.15 μm). Emitter dopings of moderate concentrations are considered to avoid any dead layer and bandgap narrowing effects. Base dopings in the range of 1 to 2x10<sup>17</sup> cm<sup>-3</sup> are needed for the optimally designed cell. Front surface recombination velocities (10<sup>4</sup> cm/sec) are required to achieve the high efficiencies. This requires the development of suitable passivation layers. Present day InP cells do not have any passivation layers and SRV's are in the range of 10<sup>7</sup> cm/sec, which has been responsible for relatively low efficiencies. Minority carrier diffusion lengths in the emitter and

Table I Emitter and Base Material/Process Parameters  
for the Optimal Design of InP Solar Cell.

	p <sup>+</sup> n Structure	n <sup>+</sup> p Structure
Emitter		
Thickness, nm	150	20
Doping, cm <sup>-3</sup>	10 <sup>18</sup>	10 <sup>18</sup>
Front SRV, cm/sec	10 <sup>4</sup>	10 <sup>4</sup>
Diffusion Length, μm	2	0.1
Lifetime, nsec	0.73	0.1
Mobility, cm <sup>2</sup> /V sec	2123	39
Base		
Thickness, μm	5	5
Doping, cm <sup>-3</sup>	10 <sup>17</sup>	10 <sup>17</sup>
Back SRV, cm/sec	10 <sup>7</sup>	10 <sup>5</sup>
Diffusion Length, μm	5	20
Lifetime, nsec	151.5	56
Mobility, cm <sup>2</sup> /V sec	63	2772
Grid Coverage Loss, %	0	0
Series Resistance, ohm cm <sup>2</sup>	0.1	0.1
Double Layer AR Coating, nm	50 (ZnS)/ 100 (MgF <sub>2</sub> )	50 (ZnS)/ 100 (MgF <sub>2</sub> )

base are also very critical in controlling the cell efficiency and can be improved by better quality material growth. For p<sup>+</sup>n cell optimal design, electron and hole diffusion lengths of 2 and 5 μm are required. Minority carrier lifetimes which would yield diffusion lengths of similar order have recently been measured on n and p type InP substrates by photoluminescence technique (ref. 5). In the case of n<sup>+</sup>p cell design, minority carrier diffusion length in the base on the order of 20 μm is required to achieve optimal efficiency. Electron diffusion lengths as high as 30 μm in n<sup>+</sup>p InP cells have been estimated from the red quantum efficiency (ref. 6). The solar cell design calculations are performed assuming zero front contact shadowing loss, 0.1 ohm cm<sup>2</sup> series resistance and two layer ZnS/MgF<sub>2</sub> antireflection coating. Zero contact shadowing loss assumes the availability of a prismatic cell cover, which helps in diverting the incoming light from grid lines on to the cell active area. This assumption also helps in considering a lower value of series resistance, because larger portion of cell could be covered by metal grid lines. In Fig. 1 and 2 we have also plotted the calculated I-V characteristics (dotted line curves) assuming grid coverage (i.e. no

prismatic covers) and higher series resistance. The  $p^+n$  results (dotted line) shown in Fig. 1 are for grid coverage of 5% and series resistance of  $0.3 \text{ ohm cm}^2$ . The  $n^+p$  results (dotted line) shown in Fig. 2 are for grid coverage of 4% and series resistance of  $0.2 \text{ ohm cm}^2$ . It is observed that one could achieve better series resistance in  $n^+p$  structures than  $p^+n$ . From these results it is observed that the open circuit voltage values remain almost the same, but the cell efficiency reduces due to grid coverage losses and the corresponding increased series resistance. However, even in this case  $p^+n$  and  $n^+p$  cell efficiencies as high as 24.8 and 23.5% respectively are predicted. In all the calculations reported in this work the InP bandgap energy of 1.35 eV and an average value of intrinsic concentration ( $n_i$ ) of  $8 \times 10^6 \text{ cm}^{-3}$  (ref. 6) have been used. It is important to point here that there exist an uncertainty in the value of  $n_i$  and various researchers have used different values.

In Fig. 3 we have shown the comparison of the calculated I-V characteristics for the optimally designed  $n^+p$  and  $p^+n$  configurations assuming the parameters of Table I. From Fig. 3 it is clear that one

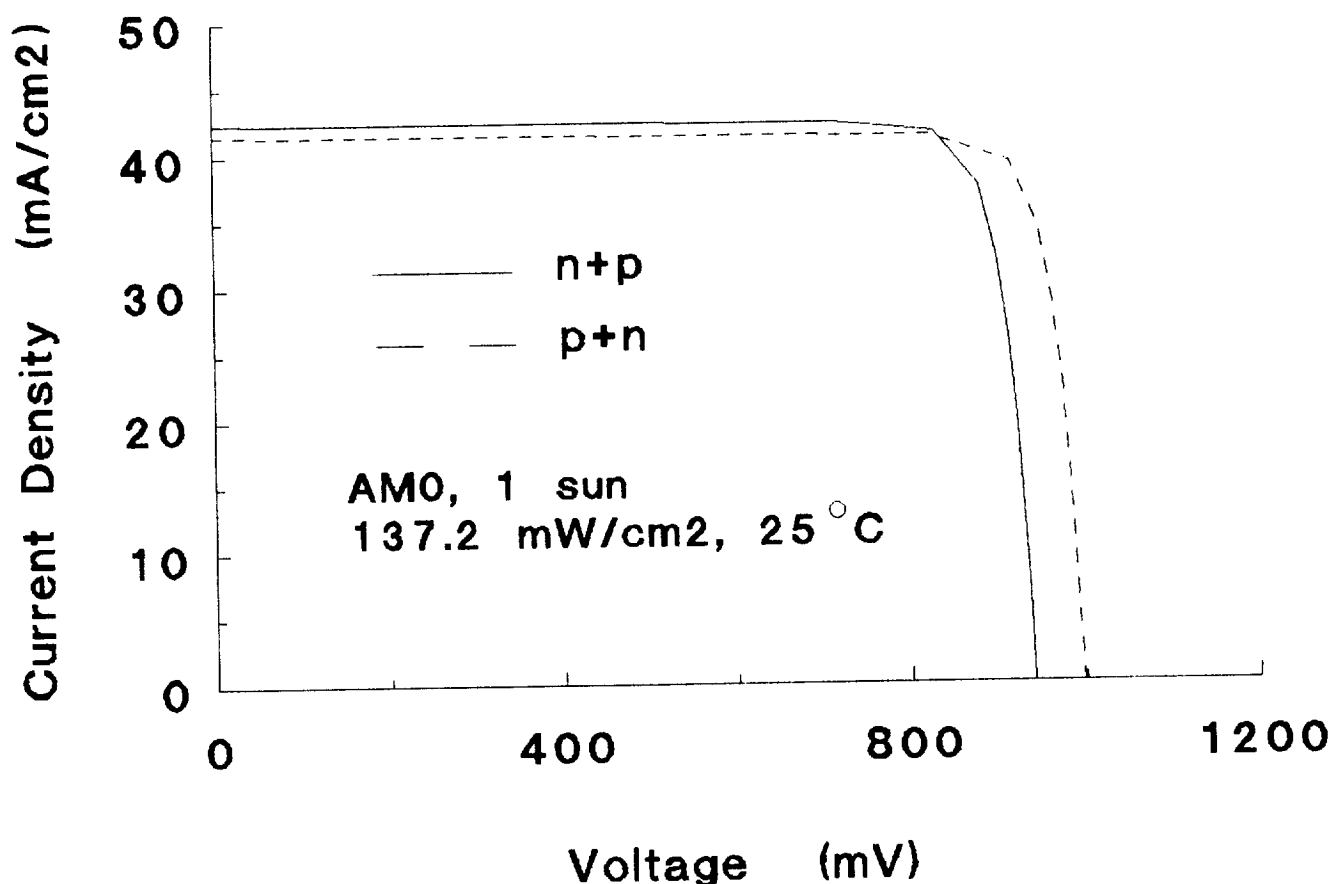


Fig. 3 Comparison of the I-V Characteristics of the Optimally Designed  $p^+n$  and  $n^+p$  InP Solar Cell Structures (Grid Shadowing Loss 0%, Series Resistance  $0.1 \text{ ohm cm}^2$ ).

could achieve higher efficiencies in  $p^+n$  configuration compared to  $n^+p$ , due to higher open circuit voltage even though the short circuit current density is somewhat lower as compared to  $n^+p$  structure. Similar observation is true, even when the effect of grid shadowing loss is considered (dotted curves of Fig. 1 and 2).

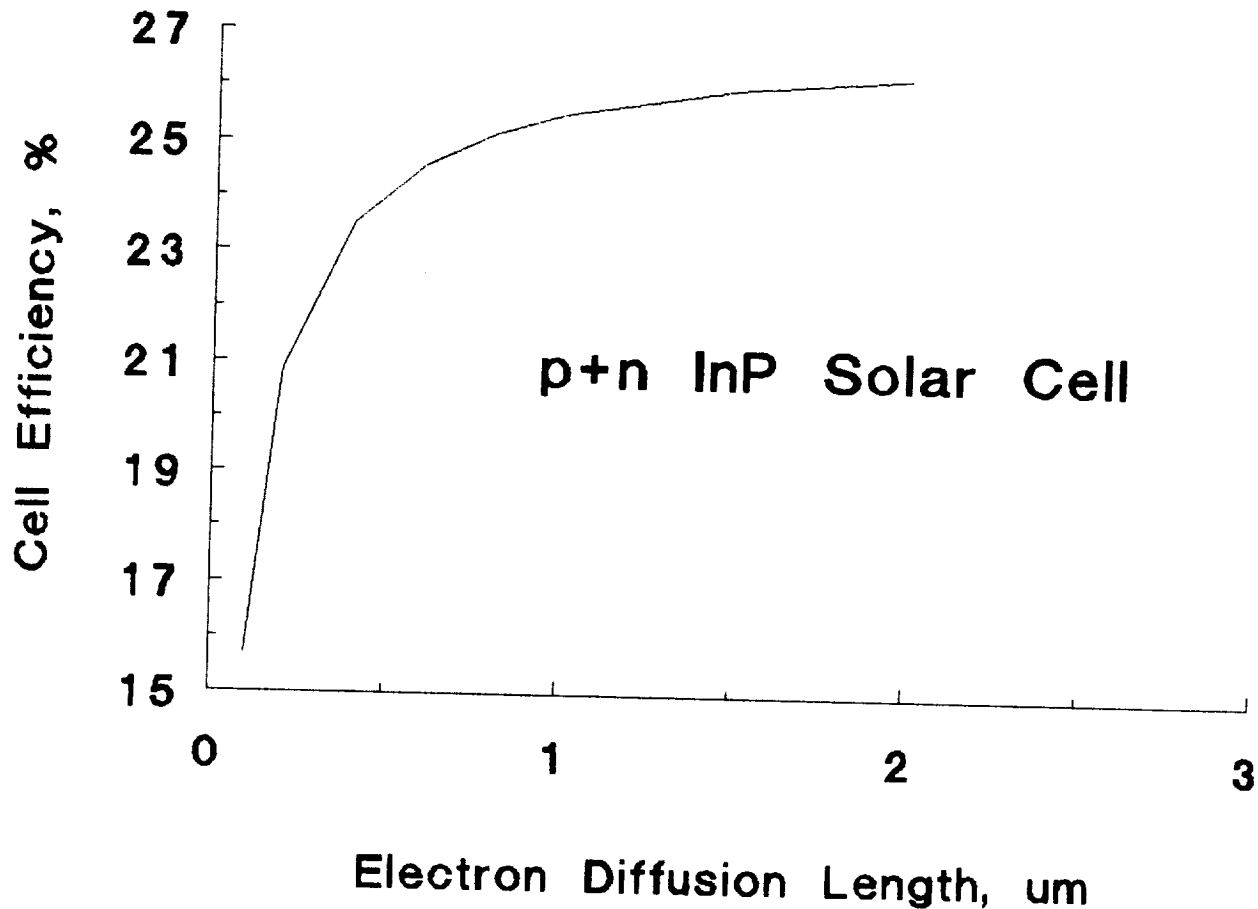


Fig. 4 Effect of Electron Diffusion Length on the  $p^+n$  InP Solar Cell AM0 Efficiency.

Minority carrier diffusion lengths in the emitter and base regions greatly influence the cell efficiency. Figures 4 and 5 describe the effect of electron and hole diffusion length respectively on the  $p^+n$  InP solar cell efficiency. These results have been obtained by varying the minority carrier diffusion length of interest and keeping all other parameters constant as per Table I. From Figs. 4 and 5 we observe that the cell efficiency vs minority carrier diffusion length curve starts saturating for electron diffusion length of 2  $\mu m$  and hole diffusion length of 5  $\mu m$  respectively. This observation allowed us to choose these values in the optimal design of  $p^+n$  InP solar cell. Longer minority carrier diffusion lengths could be obtained by improving the material growth and cell process techniques.

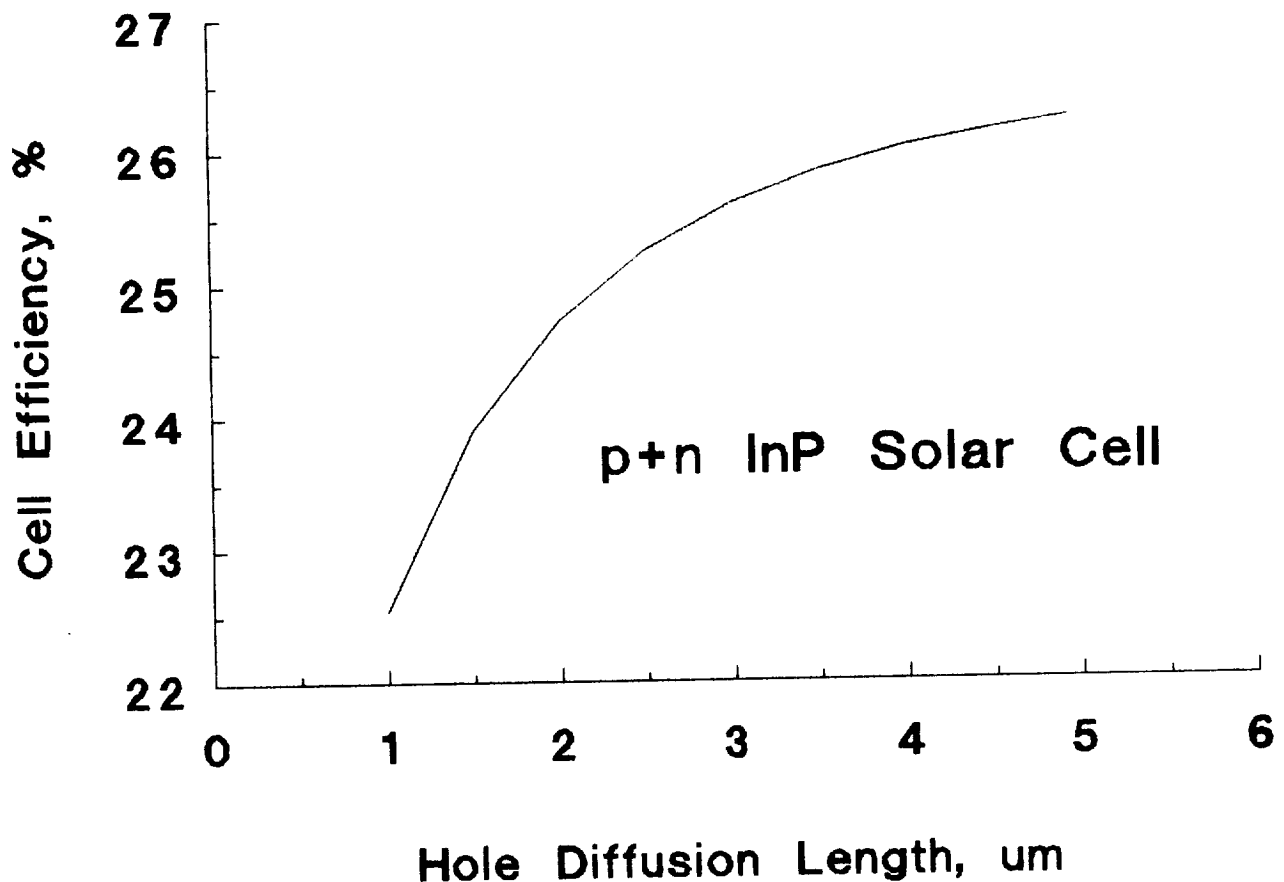


Fig. 5 Effect of Hole Diffusion Length on the p+n InP Solar Cell AM0 Efficiency.

InP solar cells have shown superior radiation resistance (ref. 7,8) as compared to GaAs and Si cells. This would lead to higher end-of-life (EOL) efficiencies. This is an important criterion as space solar arrays are designed on the basis of EOL efficiencies. In Fig. 6 we have plotted the normalized efficiency results as a function of 1 MeV electron fluence for n+p and p+n structures reported independently by Yamaguchi et al. (ref. 9), and Weinberg et al. (ref. 10). From Fig. 6 it is observed that the results reported by these two groups are conflicting as to which structure is better under electron irradiation. To date limited work on the development of p+n cells has been initiated. This has also restricted electron irradiation studies on such cells. No proton irradiation results have been reported for p+n cells. However, it is important to note that the cells used to obtain the results plotted in Fig. 6 were made from different material growth and cell process techniques. A meaningful comparison would require both types of cells to be processed under identical conditions. It is also observed that the cells used in reference 9 are more radiation resistant at the lower fluence than the cells used in reference 10, but degrade rapidly in the  $10^{15} - 10^{16} \text{ cm}^{-2}$  electron fluence range. The efficiency measure-

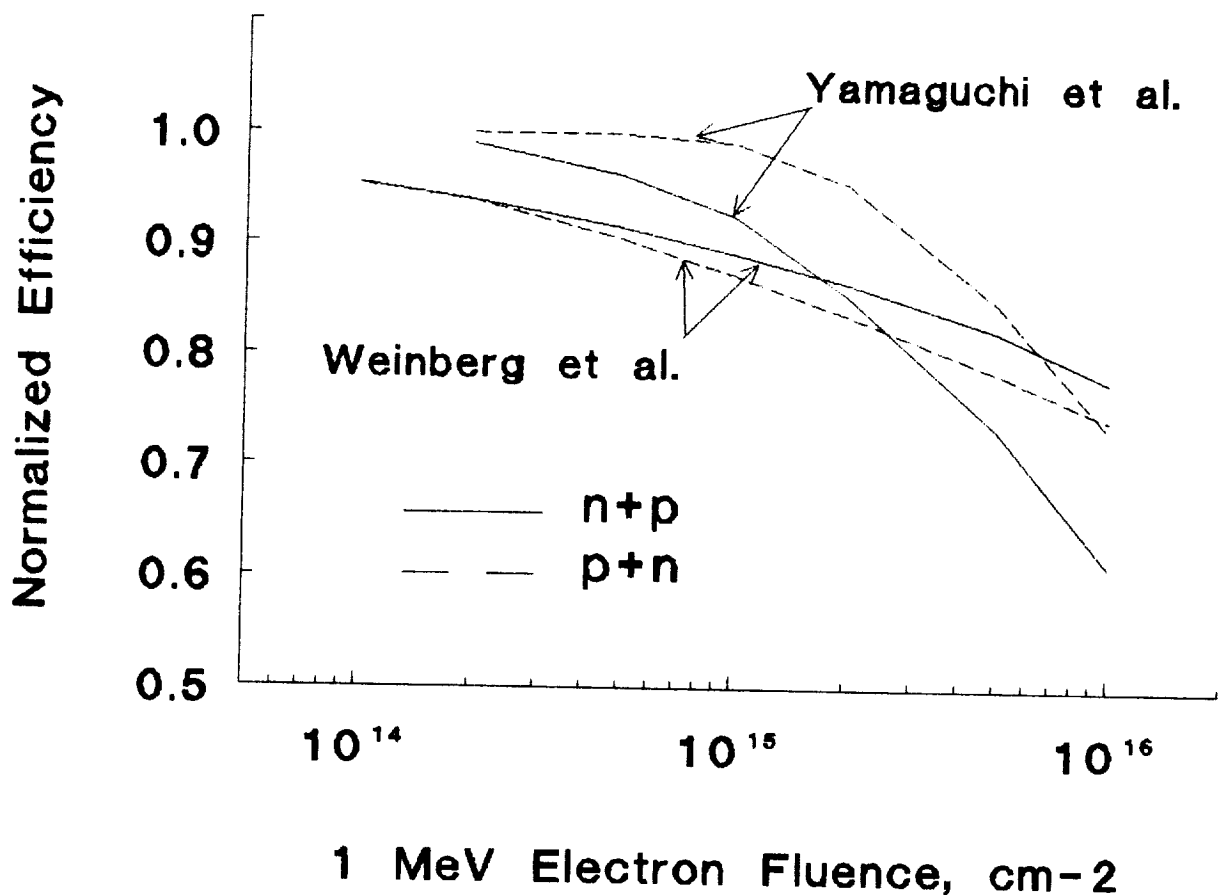


Fig. 6 Effects of 1 MeV Electron Irradiation on the Normalized Efficiency of p+n and n+p InP Solar Cells.

ment results of reference 9 are made under AM1.5 spectrum (100 mW/cm²), while reference 10 uses AM0 spectrum (137.2 mW/cm²). The discrepancy between the comparative results in Fig. 6, suggests a need for a systematic work on the electron and proton irradiation damage on these two types of cell configurations.

#### CONCLUSIONS

Optimal design calculations for the p+n and n+p indium phosphide solar cells have been performed using a computer code PC-1D. It is shown that AM0 cell efficiencies in excess of 23% at 25°C are possible. The optimal cell material and process parameters have been given. Surface passivation and improved material growth techniques require serious attention in order to obtain the minimum possible surface recombination velocities and maximum possible minority carrier diffusion lengths. Comparison of p+n and n+p cell configurations has shown that p+n offers better efficiency due to higher open circuit voltage as compared to n+p configuration. The effect of minority carrier diffusion length on InP cell efficiency has been studied. Extensive and systematic electron and proton irradiation damage studies are required. Enhanced and renewed efforts are needed to develop p+n type InP cells.

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